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Remote sensing and forest inventory for wildlife habitat assessment

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ABSTRACT

Researchers and managers undertaking wildlife habitat assessments commonly require spatially explicit environmental map layers such as those derived from forest inventory and remote sensing. However, end users of geospatial products must often make choices regarding the source and level of detail required for characterizing habitat elements, with few published resources available for guidance. We appraised three environmental data sources that represent options often available to researchers and managers in wildlife ecological studies: (i) a pre-existing forest inventory; (ii) a general-purpose, single-attribute remote sensing land cover map; and (iii) a specific-purpose, multi-attribute remote sensing database. The three information sources were evaluated with two complementary analyses: the first designed to appraise levels of map quality (assessed on the basis of accuracy, vagueness, completion, consistency, level of measurement, and detail) and the second designed to assess their relative capacity to explain patterns of grizzly bear (*Ursus arctos*) telemetry locations across a 100,000-km^2 study area in west-central Alberta, Canada. We found the forest inventory database to be reasonably functional in its ability to support resource selection analysis in regions where coverage was available, but overall, the data suffered from quality issues related to completeness accuracy, and consistency. The general-purpose remote sensing land cover product ranked higher in terms of overall map quality, but demonstrated a lower capacity for explaining observed patterns of grizzly bear habitat use. We found the best results using the specific-purpose, multi-attribute remote sensing database, and recommend that similar information sources be used as the foundation for wildlife habitat studies whenever possible, particularly those involving large areas that span jurisdictional boundaries.

1. Introduction

Contemporary strategies for wildlife habitat mapping (Boyce and McDonald, 1999), biodiversity analysis (Scott et al., 1993), and animal movement modeling (Bian, 2001) require the use of spatially explicit environmental map layers, such as those derived from land inventory databases and remote sensing. These data are commonly processed for a variety of environmental attributes, including vegetation cover (Carroll et al., 1999; McClain and Porter, 2000), land use (Osborne et al., 2001; Dash Sharma et al., 2004), landscape structure (Ripple et al., 1997; Hansen et al., 2001), and phenology (Verlinden and Masogo, 1997; Leimgruber et al., 2001), and form part of the foundation for derived habitat models and other information products designed to support research and management initiatives. The extent to which wildlife studies have come to rely on these remote sensing-based products is illustrated by Glenn and Ripple's (2004) survey of 44 such works published in *The Journal of Wildlife Management* between 2000 and 2002. The common assumption underlying these efforts is that the chosen environmental map layers are an effective representation of the natural landscape, and provide an appropriate source of information for the given application. The validity of these assumptions is an active research issue, and the topic of on-going concern within the scientific and resource management communities (Roloff and Kernohan, 1999; Glenn and Ripple, 2004; Flemming et al., 2004; Thogmartin et al., 2004).

Researchers and managers selecting the environmental information layers upon which to base their projects must often choose

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between adapting existing information sources and generating custom products of their own. Many jurisdictions maintain detailed forest inventory databases designed to aid in the management and conservation of public lands. The Alberta Vegetation Inventory [AVI] (Alberta Environmental Protection, 1991), Vegetation Resource Inventory of British Columbia (Ministry of Sustainable Resource Management, 2002), and Forest Resource Inventory of Ontario (Ontario Ministry of Natural Resources, 2001) are examples of Canadian vegetation resource inventories that are undertaken in support of integrated forest management. These types of vegetation inventory databases offer an attractive alternative for many wildlife studies because (i) they reduce or eliminate the cost and burden of production, (ii) they are often highly detailed at relatively large spatial scales (e.g. nominally 1:20,000), and (iii) they are usually distributed in convenient geographic information system [GIS] formats. However, the utility of these data sets for application to wildlife studies may be limited by issues of consistency, accuracy, age, and availability.

Concerns regarding the suitability of existing vegetation resource inventory datasets have prompted many wildlife studies to produce their own environmental information from satellite or airborne remote sensing products, particularly for projects involving large areas (e.g. Scott et al., 1993) that stretch across jurisdictional boundaries. The strategy is tempting, given the allure of generating high-quality information directly suited to the needs of the study. However, the challenges associated with effectively integrating remote sensing into multidisciplinary projects are daunting (McDermid et al., 2005), and the potential for mistakes is high. Glenn and Ripple (2004) pointed out the lack of widely accepted standards surrounding the use of digital maps of environmental attributes in wildlife habitat-mapping studies, and the differences resulting from the use of spatial data from different sources. A wide variety of remote sensing-based information products are available, ranging from relatively inexpensive land cover maps generated with well-known unsupervised classification techniques (e.g. Townshend and Justice, 1980; Franklin and Wulder, 2002) to complex and expensive multi-attribute databases produced through sophisticated mapping and modeling procedures (e.g. Franklin et al., 2000). Depending on the approach and strategy adopted, the remote sensing portion of a research or management program can range from a relatively minor component to a major consumer of project resources.

Even with the necessary resources in place, many questions remain: Which information source is most suitable? Are pre-existing inventory databases up to the task? If new information from remote sensing is necessary, must a sophisticated environmental dataset be developed, or would a less complicated land cover map provide a suitable (and less costly) alternative? To help address these questions, we examined 3 sources of environmental information: (i) a pre-existing vegetation resource inventory, (ii) a general-purpose, single-attribute remote sensing land cover map; and (iii) a specific-purpose, multi-attribute remote sensing database. The goal was to evaluate the utility of three environmental data sources that represent options commonly available to modern wildlife researchers and managers. The evaluation was accomplished with two complementary analyses: the first designed to appraise the quality of the three data sets, and the second designed to explore their relative capacity to explain patterns of grizzly bear (*Ursus arctos*) habitat selection.

2. Materials and methods

2.1. Study area

The study area was located in the west-central portion of Alberta, Canada (Fig. 1), along the front range of the Rocky Mountains. This expansive region covers more than 100,000 km^2 and encompasses one of western Canada's most physiographically and biologically diverse landscapes, including five of the province's six natural regions (Natural Regions Committee, 2006): Boreal Forest, Rocky Mountain, Foothills, Parkland, and Grassland. The area is internationally recognized for the quality of its physical and biological systems, and contains a number of provincially and federally protected reserves, including Banff and Jasper National Parks. Outside of these well known protected areas, however, the area is subject to rapid human-induced changes and extensive resource extraction. Oil and gas development, forestry, mining, and agriculture form the foundation of Alberta's economy, and exert a profound influence on the region's natural and political landscape. This apparent dichotomy places tremendous pressure on management agencies, which must balance the demands of economic activity with the obligations of ecological sustainability.

The study area is also the site of The Foothills Research Institute Grizzly Bear Research Program [FRIGBRP], a multi-agency collaboration designed to provide land managers with the necessary knowledge and planning tools to ensure the long-term conservation of grizzly bears in the province of Alberta (Stenhouse, 2005).

2.2. Data sources

Environmental data source #1: The Alberta Vegetation Inventory (pre-existing inventory data). The Alberta Vegetation Inventory [AVI] is the provincial standard for forest inventory on Alberta's public lands (Alberta Environmental Protection, 1991), and embodies the GIS-based inventory products that serve forest resource managers in many jurisdictions. Generated through manual interpretation of aerial photographs, the AVI is produced by provincial and private photo-interpretation experts who map polygon-based land parcels on the basis of tone, texture, pattern, size, shape, shadow, and association. Once delineated, these polygons are assigned attributes associated with timber productivity, moisture regime, crown closure, height, tree species composition, and age (Alberta Environmental Protection, 1991). Attributes are generated through a blend of ground reference information and the judgment of professionally certified air photo interpreters. The quality and consistency of the AVI is maintained through field checks and provincial audits, but the information's explicit accuracy levels are not quantitatively reported. Overall, the polygonal format of the data is designed primarily to suit integrated forest and resource vegetation management needs at the stand scale down to a 2-ha minimum mapping unit. This level of forest structural information is unsurpassed by any other large-area information source in the region, and the AVI forms the basis of virtually all forest management decisions on Alberta's public lands.

Environmental data source # 2: The Earth Observation for Sustainable Development of Forests derived from the Alberta Ground Cover Characterization (general-purpose land cover classification). The Earth Observation for Sustainable Development of Forests [EOSD] is a project directed at the production of a land cover map of the forested areas of Canada based on Landsat Thematic Mapper data (Wulder et al., 2003). The project was devised by Natural Resources Canada in conjunction with the Canadian Space Agency, and was undertaken in partnership with provincial agencies, universities, and non-government organizations across the country. The land cover product was devised as a general-purpose land cover map that could provide information to meet national information needs, such as the National Forest Inventory and forest carbon accounting (Wulder et al., 2004), while also serving as a standard product for regional land cover change studies and a support tool for fire prediction and management. In Alberta, a similar land cover mapping project called the Alberta Ground Cover Characterization [AGCC] had been initiated with Alberta

Sustainable Resource Development and other partners. Classification strategies and resource funding between EOSD and AGCC were integrated, and a legend translation scheme devised to derive EOSD land cover from the AGCC (hereinafter referred to as EOSD–AGCC).

The AGCC mapping protocol employs a *hierarchical classification* strategy in which unsupervised classification/hyper-clustering techniques are used to derive land cover information from among 45 spectral classes. The approach proceeds iteratively, beginning with known features such as roads, water bodies, clear cuts, and burns, and moves systematically through increasing levels of detail. Imagery used in production of AGCC maps come from the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) instruments; maps of the current study area were derived from 5 ETM+ scenes acquired from 1999 to 2002. The minimum mapping unit for EOSD–AGCC unit was 30 m $\times$ 30 m.

Environmental data source #3: The Foothills Research Institute Grizzly Bear Research Program (specific-purpose, multi-attribute remote sensing database). The FRIGBRP has been conducting field work in the study area since 1999, resulting in an extensive collection of ground plots that have enabled the generation of a sophisticated series of remote sensing-based map products comprised of 4 layers: land cover, crown closure, species composition, and leaf area index [LAI] phenology. The database was generated from a multi-source digital dataset using a variety of supervised mapping and modeling techniques described fully by McDermid (2006). While produced separately, the 4 layers are spatially integrated within a GIS framework that results in a flexible information source capable of supporting a broad range of resource management objectives, including grizzly bear habitat mapping within the FRIGBRP project (e.g. Nielsen et al., 2003; Nielsen, 2004). The FMFGPRP map layers were generated with data from Landsat TM and the Moderate Resolution Imaging Spectroradiometer [MODIS], as well as topographic derivatives from a digital elevation model. The land cover component of the information base was derived using object-based classification procedures in Definiens Professional. Species composition and arcsine-transformed crown closure were modeled in S-PLUS using binomial-family generalized linear models and conventional regression models, respectively. The minimum mapping unit was 30 m $\times$ 30 m for land cover, crown closure, and species composition products, and 250 m $\times$ 250 m for LAI products.

Grizzly bear use/availability data. The FRIGBRP has assembled an extensive database of telemetry locations designed to help characterize the selection of resources by grizzly bears in western Alberta. Between 1999 and 2004, 78 individual bears were captured using aerial darting and snaring techniques (Hobson, 2005). Of these, 64 animals were fitted with Televilt or Advanced Telemetry Systems global positioning system [GPS] radio collars programmed to acquire positional fixes at intervals ranging from 1 to 4 h. All capture and collaring efforts followed procedures reviewed and revised by the Canadian Council on Animal Care for the safe handling of bears. Our research protocols were further approved by the Animal Care Committee at the Western College of Veterinary Medicine in Saskatoon, Saskatchewan and adhered to the "Protocol for the use of drugs in Wildlife Management in Alberta" (May 9, 1997). All capture and handling methods also were consistent with the guidelines of the American Society of Mammalogists (Animal Care and Use Committee, 1998).

For the purposes of this study, we restricted the raw data to include only individuals that generated a minimum of 50 telemetry positions (Leban et al., 2001) and that remained within the boundaries of the study area. The resulting dataset consisted of 35,572 point locations from 34 female and 19 male bears.

We stratified the telemetry data into 3 time periods – hypophagia (May 1 to June 15), early hyperphagia (June 16 to August 15), and late hyperphagia (August 16 to October 15) – to account for seasonal variations in habitat use, defined on the basis of previously observed food habits and selection patterns (Pearson and Nolan, 1976; Nielsen et al., 2003). To characterize the resources available to the GPS-collared grizzly bears used in this study, we defined their home ranges using multi-annual 100% minimum convex polygons [MCPs] within the Hawth's Tools extension in ArcGIS (Beyer, 2004). A random point generator was used to select random samples within MCP home ranges at a density of roughly 5 points per square kilometer. Together with the grizzly bear telemetry locations, these data comprise the *presence* and *available* information suitable for both individual and population level resource selection analyses (Manly et al., 2002).

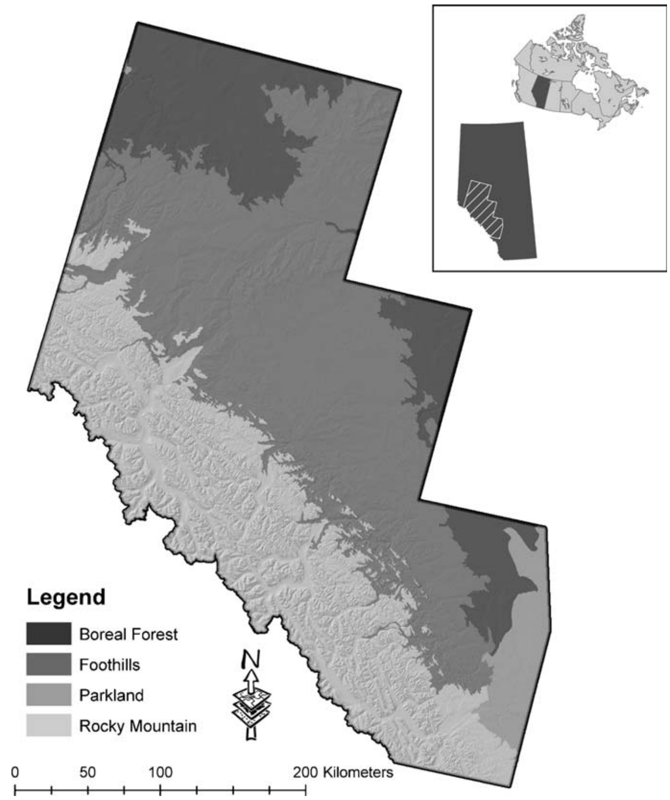

Fig. 1. Location of study area in western Alberta, Canada.

2.3. Map quality assessment

Assessing the quality of geographic information is a complex topic, whose details in the literature are somewhat obscured by multiple definitions and limited consensus (Mowrer, 1999; Duckham et al., 2001). Suffice to say that no observation or representation of natural phenomenon is perfect, and uncertainty in one form or another is always a part of geographic information (Couclelis, 2003). The quality of a spatial data set is a broad issue that can relate to a variety of properties (Duckham et al., 2001; Duckham et al., 2006). Map accuracy, defined here as the deviation of recorded values from true values, is the property that receives the most attention (e.g. Foody, 2002), but a complete quality assessment should also incorporate other elements of imperfection. Vagueness (poor expression, causing incoherence in meaning), consistency (agreement or logical coherence across the spatial extent of the map), completeness (no missing parts or unmapped areas), level of measurement (nominal, ordinal, interval, ratio), and detail (number of attributes measured) all affect the quality of geographic information, and should be considered where possible.

Table 1
Land cover and structural vegetation classes used to provide baseline accuracy data used in the map quality assessment. Tree species composition is defined as the proportion of basal area or stem count occupied by each forest type. Crown closure is the proportion of ground (when viewed from above) or sky (when viewed from below) obscured by tree canopy. Ecological moisture regime is a relative ranking of sites based on their available moisture supply, and includes dry (rapidly drained), mesic (moderately well-drained), wet (poorly drained to flooded where the water table is at or near the surface), and aquatic (permanent deep water).

Class label	AVI	EOSD–AGCC	FRIGBRP
(1) Closed coniferous forest	>60% crown closure; >75% conifer, based on basal area; 'dry' or 'mesic' moisture regime	>50% crown closure; >80% conifer, based on stem count; 'dry' or 'mesic' moisture regime	>50% crown closure; >80% conifer, based on stem count; 'dry' or 'mesic' moisture regime
(2) Open coniferous forest	6–59% crown closure; >75% conifer, based on basal area; 'dry' or 'mesic' moisture regime	6–49% crown closure; >80% conifer, based on stem count; 'dry' or 'mesic' moisture regime	6–49% crown closure; >80% conifer, based on stem count; 'dry' or 'mesic' moisture regime
(3) Closed broadleaf forest	>60% crown closure; >75% broadleaf, based on basal area; 'dry' or 'mesic' moisture regime	>50% crown closure; >80% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime	>50% crown closure; >80% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime
(4) Open broadleaf forest	6–59% crown closure; >75% broadleaf, based on basal area; 'dry' or 'mesic' moisture regime	6–49% crown closure; >80% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime	6–49% crown closure; >80% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime
(5) Closed mixedwood forest	>60% crown closure; 26–74% broadleaf, based on basal area; 'dry' or 'mesic' moisture regime	>50% crown closure; 26–79% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime	>50% crown closure; 26–79% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime
(6) Open mixedwood forest	6–59% crown closure; 26–74% broadleaf, based on basal area; 'dry' or 'mesic' moisture regime	6–49% crown closure; 26–79% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime	6–49% Crown closure; 26–79% broadleaf, based on stem count; 'dry' or 'mesic' moisture regime
(7) Upland shrubs	>25% shrub cover; <6% tree cover; 'dry' or 'mesic' moisture regime	>25% shrub cover; <6% tree cover; 'dry' or 'mesic' moisture regime	>25% shrub cover; <6% tree cover; 'dry' or 'mesic' moisture regime
(8) Upland herbaceous	<25% shrub cover; <6% tree cover; 'dry' or 'mesic' moisture regime	<25% shrub cover; <6% tree cover; 'dry' or 'mesic' moisture regime	<25% shrub cover; <6% tree cover; 'dry' or 'mesic' moisture regime
(9) Treed wetland	>6% crown closure; 'wet' or 'aquatic' moisture regime	>6% crown closure; 'wet' or 'aquatic' moisture regime	>6% crown closure; 'wet' or 'aquatic' moisture regime
(10) Open wetland	<6% crown closure; 'wet' or 'aquatic' moisture regime	<6% crown closure; 'wet' or 'aquatic' moisture regime	<6% crown closure; 'wet' or 'aquatic' moisture regime
(11) Water	>6% standing or flowing water	>6% standing or flowing water	>6% standing or flowing water
(12) Barren land	<6% vegetation cover	<6% vegetation cover	<6% vegetation cover

We evaluated map accuracy using 245 independent, randomly selected test sites surveyed in the field by trained personnel. To establish a consistent baseline for comparing the three information sources, we produced a series of *derived* map products based on land cover and structural vegetation attributes common to all three data sources (Table 1). While the derived maps represented a simplification of the original products that did not include some attributes that were unique to individual sources (for example, the *height* and *age* information contained in the AVI, or the *leaf area index* [LAI] attributes of the FRIGBRP information base), this was necessary to create a common framework for baseline evaluation. Since the AVI was not available for the entire study area, its accuracy was assessed with a reduced set of 175 sample points. Observations were made on the basis of contingency tables and basic summary statistics such as percent accuracy and the kappa statistic (Cohen, 1960). Other map quality attributes – vagueness, consistency, completeness, level of measurement, and detail – that are not as amenable to detailed statistical analyses were summarized either qualitatively or with simple counts and summary statistics.

2.4. Resource selection analysis

We constructed a series of resource selection functions [RSFs] in the statistical package S-Plus using binary logistic regression to provide a quantifiable means of judging the relative utility of the three candidate information sources as foundations for supporting grizzly bear habitat research and operational management objectives. We did not evaluate the derived (i.e. simplified) map products for this portion of the analysis, since the goal here was to assess relative capacity of the three information bases to explain patterns of grizzly bear habitat selection. With this purpose in mind, it is precisely the *differences* in the three candidate sources (including the added data elements available in FRIGBRP and AVI) whose value we were trying to assess.

We performed analyses of the three candidate information sources at both the population and individual levels – the "Design I" and "Design III" approaches of Manly et al. (2002), respectively – to illuminate potential differences with respect to scale. Separate models were developed for male and female bears during each of the 3 observed time frames: hypophagia, early hyperphagia, and late hyperphagia. We used a stepwise procedure based on Akaike's Information Criterion [AIC] (Burnham and Anderson, 1998) to develop the minimum adequate models, with decisions confirmed through chi-square tests and analyses of variance. Candidate models were constructed using variables from each of the 3 data sets separately, and evaluated against each other using the AIC statistic and null/residual deviance.

A complicating factor at both levels of analysis was the incomplete availability of the AVI within the study area. Since resource selection cannot be properly analyzed using incomplete environmental data, it was necessary to create 2 separate presence/absence subsets: one composed of data from all the bears, for which only remote sensing information from EOSD–AGCC and FRIGBRP was available, and the second comprised of data from bears whose home ranges included complete AVI coverage, for which information from all 3 environmental data sources was available. Since grizzly bears – particularly males – occupy such large home ranges, the *AVI-available* subset was substantially reduced from the original, containing just 14 of 34 females and 1 of 19 males, constrained almost exclusively to the central foothills portion of the study area. Therefore, we carried out

Table 2
Summary of land cover class accuracies (Producer's), overall accuracy, and Kappa statistic for derived maps based on 3 candidate data sources. Note that individual accuracy statistics for classes with less than $n < 10$ (labeled *) are likely under-sampled and should be interpreted with caution.

Class label	AVI		EOSD–AGCC		FRIGBRP	
	n	Accuracy (%)	*n*	Accuracy (%)	*n*	Accuracy (%)
(1) Closed coniferous forest	38	60.5	57	96.5	57	89.5
(2) Open coniferous forest	7	71.4[a]	8	25.0[a]	8	62.5[a]
(3) Closed broadleaf forest	17	41.2	17	70.6	17	76.5
(4) Open broadleaf forest	1	100[a]	1	0[a]	1	100[a]
(5) Closed mixedwood forest	29	13.8	33	24.4	33	69.7
(6) Open mixedwood forest	0	–	0	–	0	–
(7) Upland shrubs	17	29.4	26	38.5	26	73.1
(8) Upland herbaceous	23	39.1	28	71.4	28	75.0
(9) Treed wetland	15	53.3	15	40.0	15	53.3
(10) Open wetland	8	25.0[a]	8	62.5[a]	8	50.0[a]
(11) Water	4	100[a]	11	81.8	11	100
(12) Barren land	16	68.8	41	75.6	41	85.4
Overall (%)		45.1		64.5		78.0
Kappa		0.40 (fair)		0.60 (moderate)		0.75 (good)

[a] Individual accuracy for these classes should be interpreted with caution.

the population level analyses twice: once on the reduced dataset, for which all three candidate information sources were evaluated, and once on the complete dataset, for which only the AGCC and FRIGBRP sources were evaluated. At the individual level, we selected 5 bears from the reduced dataset to form the basis for evaluation of all three candidate information sources.

3. Results

3.1. Map accuracy

The FRIGBRP generated the highest map accuracy (78%, Kappa = 0.75), followed by the EOSD–AGCC (65%, Kappa = 0.60), and the AVI (45%, Kappa = 0.40; Table 2). The accuracies of individual (Producer's) cover classes varied widely for each data source, but should be interpreted with caution due to low sample sizes in some classes. We limit our comments to overall map accuracies and individual classes with larger numbers of samples.

While generally producing the highest overall results, the FRIGBRP map tended to over-estimate crown closure. We found the pure conifer (90%) and broadleaf (77%) classes to be well separated, but some of the mixedwood sites were mislabeled as pure. Shrub and upland herbaceous lands were predictably confused, while spectrally and topographically distinct classes such as water (100%) and barren land (86%) were differentiated consistently.

The EOSD–AGCC map performed well with spectrally unique classes such as water (82%), closed coniferous (97%), and barren lands (86%), but less consistently with categories involving tree species composition and crown closure. Open coniferous forests were over-estimated, and there was confusion when discriminating among pure broadleaf, mixedwood, and dense shrub categories.

For half the classes (6 out of 12), we observed the lowest accuracy levels with the AVI-based map product. Closed broadleaf, closed mixedwood, shrub, and herbaceous classes were all mapped with less than 50% accuracy.

3.2. Map quality assessment

Overall map quality is a function of a number of attributes, and a complete analysis requires consideration of more than just accuracy (Worboys, 1998). Table 3 summarizes the relative rank of the three data sources for each of six map quality attributes: accuracy, vagueness, completion, consistency, level of measurement, and detail. The FRIGBRP products received the best overall rank (7), followed by the EOSD–AGCC map (11), and the AVI (13).

None of the three information sources examined in this study suffered from problems related to vagueness. Metadata from each source outlined explicit class definitions, and information in all cases were related directly to physical ground phenomena.

Because the AVI provided only partial coverage of the study area, it received the lowest rank in terms of map completion. The

Table 3
Relative scores assigned to data information sources for map quality attributes, as defined in text.

	Accuracy	Vagueness	Completion	Consistency	Level of measurement	Detail	Total score (rank)
FRIGBRP	1	1	1	1	1	2	7 (1)
EOSD–AGCC	2	1	1	1	3	3	11 (2)
AVI	3	1	3	3	2	1	13 (3)

Table 4
AIC statistics, ranks, and qualifying variables of minimum adequate models for female grizzly bears at the population level. Models derived from the reduced dataset with full AVI coverage. S-1 is hypophagia (May 1 to June 15), S-2 is early hyperphagia (June 16 to August 15), and S-3 is late hyperphagia (August 16 to October 15).

	S-1				S-2				S-3			
	AIC	Δi	Rank	Variables	AIC	Δi	Rank	Variables	AIC	Δi	Rank	Variables
Female												
FRIGBRP	75,302	0	1	Land cover, LAI change	113,799	0	1	Early LAI, CC land cover	58,143	0	1	Land cover, LAI change
EOSD–AGCC	85,874	10,572	3	Land cover	118,355	4556	3	Land cover	63,006	4863	3	Land cover
AVI	75,441	139	2	Land cover, age	114,202	403	2	Density, height, age	61,127	2984	2	Age, density

Table 5
AIC statistics, ranks, and qualifying variables of minimum adequate models for male and female grizzly bears at the population level. Models derived from the full dataset with no AVI coverage. S-1 is hypophagia (May 1 to June 15), S-2 is early hyperphagia (June 16 to August 15), and S-3 is late hyperphagia (August 16 to October 15).

	S-1				S-2				S-3			
	AIC	Δi	Rank	Variables	AIC	Δi	Rank	Variables	AIC	Δi	Rank	Variables
Female												
EOSD–AGCC	215,624	16,507	2	Land cover	278,894	1280	2	Land cover	224,690	24,439	2	Land cover
FRIGBRP	199,117	0	1	Land cover, LAI change	277,614	0	1	Early LAI, land cover	200,251	0	1	Land cover, CC, LAI change
Male												
EOSD–AGCC	204,397	28,841	2	Land cover	241,102	22,537	2	Land cover	146,949	35,856	2	Land cover
FRIGBRP	175,556	0	1	Land cover, CC, early LAI	218,565	0	1	Land cover, early LAI	111,093	0	1	Land cover, LAI change

two remote sensing products, by contrast, were not restricted by jurisdictional boundaries and were therefore complete across all areas.

The AVI also received the lowest rank for map consistency. Creation and maintenance of the AVI within the study area is the responsibility of several different organizations; each of these agencies operates on a different schedule, and updates may occur only once per decade or more, resulting in noticeable differences within the finished product. While maps derived from remote sensing – particularly large-area data sets that combine multiple image scenes across time or sensors – also have the potential for significant inconsistencies, visual inspections of the EOSD–AGCC and FRIGBRP databases revealed few such issues.

We judged the EOSD–AGCC product – composed entirely of nominal- and ordinal-level classes – to have the lowest level of measurement of any information source in the analysis. The FRIGBRP database, with continuous ratio-level estimates of crown closure, species composition, and LAI had the highest level of measurement. The AVI occupies the intermediate position, recording ordinal-level estimates for crown closure, interval-level measurements of species composition and age (rounded to the nearest 10), and ratio-level estimates of height.

The AVI – with 6 main attributes – ranked the highest in terms of detail, followed by FRIGBRP (5 attributes) and EOSD–AGCC (1 attribute).

3.3. Resource selection analysis

For female bears in the reduced dataset (containing only those bears whose home ranges were covered by the AVI), FRIGBRP models produced the lowest AIC for all 3 time periods, followed by AVI and EOSD–AGCC (Table 4). There were no results for male bears at the population level, since only 1 male qualified for the reduced dataset—not enough to define a population. However, results from the EOSD–AGCC and FMFGBRP for both male and female grizzly bears at the population level were available from the complete dataset (Table 5). The patterns here were the same as those noted above, with models from the FRIGBRP being ranked consistently higher than those derived from the EOSD–AGCC. Male bears and broader populations from both the mountain and foothills regions did not seem to affect the overall pattern of results.

Models derived from the EOSD–AGCC database for the 5 selected bears at the individual level were again ranked consistently lower than those from AVI and FRIGBRP information sources (Table 6). Age, density, LAI, and crown closure were frequently selected in the final minimum adequate models, and received better AIC support than models constructed from EOSD–AGCC-derived land cover alone. However, there seems very little to choose between AVI- and FRIGBRP-based models at the individual level, with both sources contributing top-ranked models: 7 out of

Table 6
AIC statistics, ranks, and qualifying variables of minimum adequate models for selected male and female grizzly bears at the individual level.

	S-1				S-2				S-3			
	AIC	Δi	Rank	Variables	AIC	Δi	Rank	Variables	AIC	Δi	Rank	Variables
G070												
EOSD–AGCC					7,179	479	3	Land cover				
FRIGBRP					6,803	103	2	Land cover, late LAI, CC				
AVI					6,700	0	1	Land cover, density, height				
G073												
EOSD–AGCC	4,424	491	3	Land cover	7,934	453	3	Land cover	5,989	642	3	Land cover
FRIGBRP	3,933	0	1	Land cover, LAI change, CC	7,484	3	2	Land cover, LAI change, CC	5,347	0	1	Land cover, LAI change
AVI	4,136	203	2	Land cover, Age, density	7,481	0	1	Density, age, total conifer	5,429	82	2	Density, age, total conifer
G074												
EOSD–AGCC					6,072	1763	3	Land cover				
FRIGBRP					4,309	0	1	Early LAI, CC				
AVI					4,827	518	2	Density, age, total conifer				
G012												
EOSD–AGCC	23,813	372	3	Land cover	24,708	1458	3	Land cover	14,509	3205	3	Land cover
FRIGBRP	23,020	0	1	Early LAI, CC	23,250	0	1	LAI change, CC	11,304	0	1	LAI change, SC
AVI	23,392	793	2	Density, height, age	23,937	687	2	Land cover, age	12,461	1157	2	Density
G011												
EOSD–AGCC	6,281	797	3	Land cover	6,099	370	3	Land cover				
FRIGBRP	5,484	0	1	Early LAI, CC	6,009	280	2	Land cover, LAI Change				
AVI	5,737	253	2	Density, Height, Age	5,729	0	1	Density, Height, Age				

Table 7
Mean rank summary of minimum adequate models for at the individual, population, and combined (both individual and population) levels.

	Individual	Population	Overall
EOSD–AGCC	3	3	3
FRIGBRP	1.3 (1)	1	1.2 (1)
AVI	1.7 (2)	2	1.8 (2)

10 cases for FRIGBRP and 3 out of 10 for AVI. We observed no discernable patterns regarding time period related to these observations.

A summary of the mean rankings observed for RSF models at the individual and population levels combined (Table 7) showed that models from the FRIGBRP dataset were ranked first overall, followed by the AVI and EOSD–AGCC. The same pattern emerged for an overall ranking for each data source.

4. Discussion

Predictably, the results of the accuracy assessment and map quality analysis reflect the relative levels of investment in the generation of each map product. High-end remote sensing databases such as the FRIGBRP – based on large quantities of ground data, and produced using sophisticated multi-source mapping and modeling techniques – produced the best overall results. However, the cost is high for these information sources, which involve extensive field programs, specialized software, and labor costs for highly trained image processing technicians. Franklin et al. (2002) reported a cost-to-project estimate of \$2.50 km^{-2} for a similar high-end map from an earlier stage of the FRIGBRP. Maps based on pre-existing forest inventory data such as the AVI, on the other hand, cost significantly less, requiring only mid-level technical assistance for GIS data handling. However, the overall map quality may suffer from incomplete, inconsistent layers. Mid-level map products of intermediate expense can be achieved from remote sensing sources through unsupervised classification techniques exemplified by the EOSD–AGCC. High-quality technical expertise and sophisticated software are still required, but the need for expensive field data is significantly reduced.

The results of resource selection analyses suggest that *deeper* environmental databases containing information beyond categorical land cover variables are superior for explaining patterns of grizzly bear habitat use. The firm advantage of the AVI and FRIGBRP data sets over the land cover only EOSD–AGCC offering illustrates the additional explanatory power contained in datasets that include variables related to age, height, phenology, and other detailed aspects of vegetation structure. The closeness of the overall ranking of the AVI and FRIGBRP models – particularly at the individual level – suggests that one source had no clear-cut advantage over the other, and that either might serve effectively as foundations for grizzly bear research and operational management activities, depending on the scope and needs of the individual project. The major limitation of the AVI information base is its incomplete coverage, particularly in the mountain regions and with respect to male grizzly bears with extensive home ranges.

The main reason for pursuing a two-part analysis strategy – one aimed at assessing the map quality of the three information sources, and another designed to assess their relative capacity to explain grizzly bear habitat selection – was to enable us to separate *quality* from *utility*. For example, it could well be that one candidate information source produces better maps while another is more useful for supporting habitat studies. In fact this is what we observed, with the EOSD–AGCC product judged higher than the AVI in terms of map quality, but lower with respect to its capacity to explain patterns of grizzly bear habitat selection. This is a useful distinction. However, only the specific-purpose, multi-attribute information base (FRIGBRP) was observed to rank highly in both respects.

5. Conclusions

There is a general lack of guidelines governing the selection of spatially explicit environmental map layers for use in resource selection analysis and other aspects of contemporary wildlife habitat assessment. Pre-existing forest inventories derived from manual air photo interpretation, general-purpose land cover maps from classified satellite imagery, and specialized multi-attribute databases from advanced remote sensing techniques represent three options commonly available to managers and researchers, but few studies have compared the quality and utility of these various information sources. The results of our analyses show that these different data sets can be expected to display varying levels of accuracy, quality, and ability to explain patterns of wildlife habitat selection.

In general, we recommend the use of specific-purpose, multi-attribute information bases generated from empirical models integrating field measurement and satellite image data as the best platform for conducting wildlife habitat studies; particularly those operating across large, multi-jurisdictional study areas. Pre-existing vegetation resource inventories containing detailed information on forest structure, age, and productivity are capable of supporting habitat analysis in areas where they exist, but may suffer from a variety of quality issues related to availability, consistency, and accuracy at the scales commonly used in wildlife studies. General-purpose remote sensing land cover maps occupy the middle rank in terms of map quality attributes, but contain a limited capacity for explaining patterns in wildlife habitat use, and should be strengthened by incorporating additional resource variables.

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